CHAPTER 2

FROST EFFECTS

2-1. Need for considering effects of frost in pavement design. The detrimental effects of frost action in subsurface materials are manifested by nonuniform heave of pavements during the winter and by loss of strength of affected soils during the ensuing thaw period. This is accompanied by a corresponding increase in damage accumulation and a more rapid rate of pavement deterioration during the period of weakening. Other related detrimental effects of frost and low temperatures are: possible loss of compaction, development of permanent roughness, restriction of drainage by the frozen strata, and cracking and deterioration of the pavement surface. Hazardous operating conditions, excessive maintenance, or pavement destruction may result. Except in cases where other criteria are specifically established, pavements should be designed so that there will be no interruption of traffic at any time due to differential heave or to reduction in load-supporting capacity. Pavements should also be designed so that the rate of deterioration during critical periods of thaw weakening, and during cold periods causing low-temperature cracking, will not be so high that the useful life of the pavements will be less than 5 years.

2-2. Conditions necessary for ice segregation. Three basic conditions of soil, temperature, and water must be present simultaneously for significant ice segregation to occur in subsurface materials.

a. Soil. The soil must be frost-susceptible, which usually implies that under natural climatic conditions the soil moisture becomes segregated into localized zones of high ice content. To some degree, all soils that have a portion of their particles smaller than about 0.05 millimeters are frost-susceptible. Temperature, moisture availability, surcharge pressure, and density act as additional influences that modify the basic frost-susceptibility of such soils.

b. Temperature. Freezing temperatures must penetrate the soil because the phase change from water to ice is largely responsible for drawing additional water from the surrounding soil toward the growing ice mass. The amount of water stored as segregated ice is usually observed to vary inversely with the rate of advance of the freezing isotherm.

c. Water. A source of water must be available to the zone of freezing. Usually the source will be an underlying ground water table, an aquifer or infiltration through overlying layers. If the supply of water to the freezing zone is restricted by distance from the external water sources or by low soil permeability, water will be drawn from the voids of the soil adjacent to the growing ice crystal or from soil below the freezing front.

d. Interrelationship among variables. A change in one or another of the three basic factors will vary the amount of ice segregated per unit volume of soil. Natural stratigraphic variations and construction details affect the relationship among these factors and therefore also influence the amount of segregated ice. A common example is a transition from cut to fill along a right-of-way, which represents a change in subgrade soils, in the pattern of subsurface water flow, and most likely in the freezing rate.

2-3. Description of ice segregation in soils. The process of ice segregation is a complex interaction of simultaneous heat and water flow through the mass of mineral and organic particles that make up the soil. Recent research has identified three distinct zones of the freezing process. Figure 2-1 illustrates the three zones when subfreezing temperatures have penetrated into the subgrade. The amount of unfrozen water varies with the type of soil, the soil particle surface characteristics, the gradation of the soil, and the temperature. In general, finer soils contain larger amounts of unfrozen water at a given subfreezing temperature than coarser soils and for a given soil the unfrozen moisture content decreases with lower subfreezing temperatures. While moisture movement in the frozen zone makes an insignificant contribution to frost heave, moisture movement induced by negative pore pressures developed in the freezing zone has a major impact on the magnitude of frost heave.

a. The lower boundary of the freezing zone in figure 2-1 is the depth at which the temperature is equal to the freezing point of the bulk water in the soil. This temperature is generally within one or two tenths of a degree below 32 degrees F., depending upon the chemical content of the soil water.

b. The upper boundary of the freezing zone in frost-susceptible soils is generally defined as the bottom of the growing ice lens. It is at this location where the negative pore pressure causing moisture movement to the ice lens is generated. An ice lens continues to grow in thickness in the direction of heat transfer until ice formation at a lower elevation cuts off the source of water, or until available water is depleted or it approaches a level at which sub-freezing soil temperatures no longer prevail. At this point, ice will stop forming.

2-4. Frost-susceptible soil. The potential intensity of ice segregation that may occur in a freezing season is dependent to a large degree on the size-range of the soil voids, which in turn is determined by the size and size distribution of the soil grains, soil density, and particle shape and orientation. As previously mentioned, at least a portion of the grains must be sufficiently small (less than about 0.05 millimeters in diameter) so that some of the water remains as unfrozen water films, providing channels for liquid flow. For pavement design, the potential ice segregation is often expressed as an empirical function of grain size as follows. Most inorganic soils containing 3

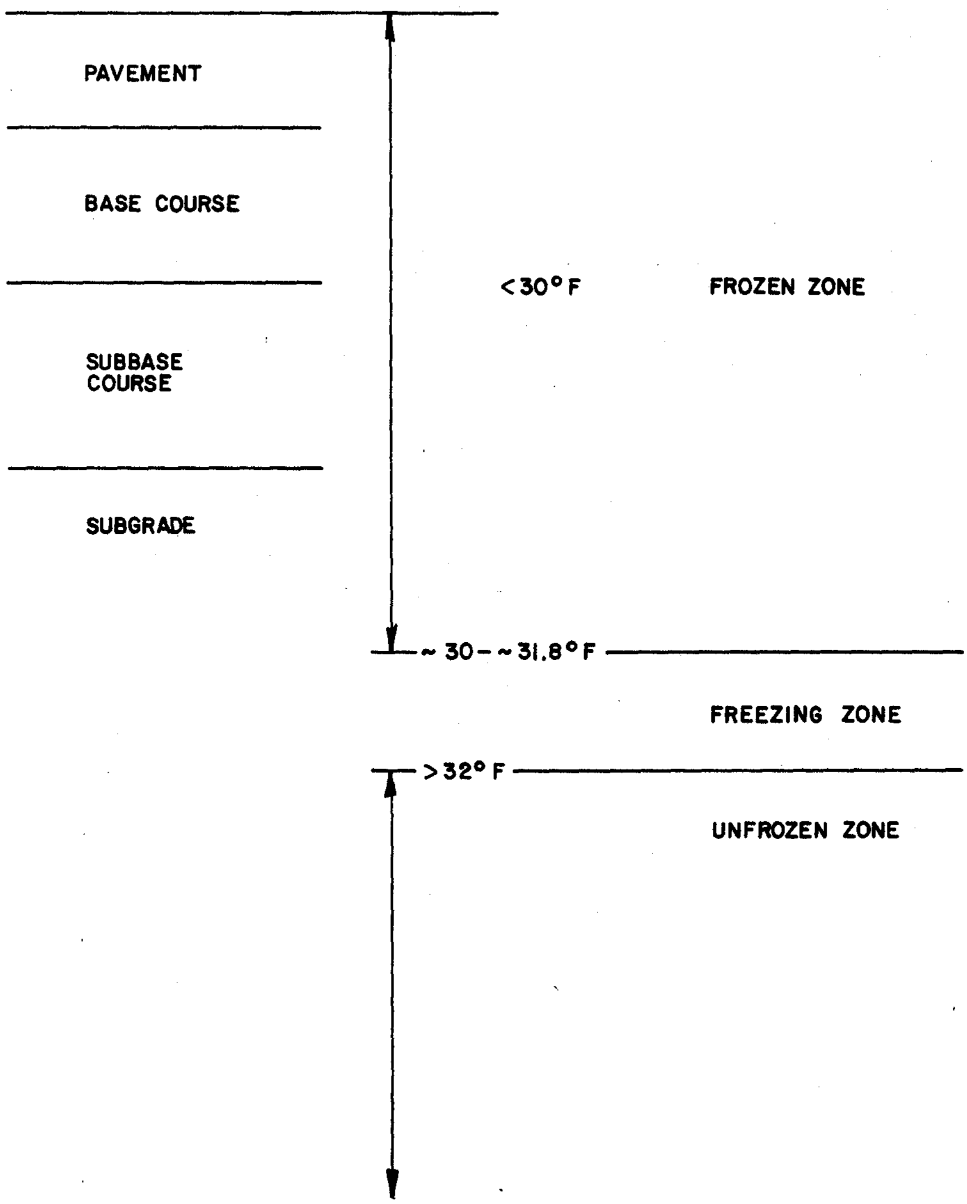

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FIGURE 2-1. FREEZING SEQUENCE IN A TYPICAL PAVEMENT PROFILE percent or more by weight of grains finer than 0.02 millimeters in diameter are frost-susceptible. Gravels, well-graded sands, and silty sands, especially those approaching the theoretical maximum density curve, that contain 1-1/2 to 3 percent of grains finer than the 0.02-millimeter size by weight should be considered as possibly frost-susceptible. Uniform sandy soils may have as much as 10 percent of their grains finer than 0.02 millimeters by weight without being frost-susceptible. However, their tendency to occur interbedded with other soils usually makes it impractical to consider them separately.

a. Standard laboratory freezing tests. Soil judged as potentially frost-susceptible under the above criteria may be expected to develop significant ice segregation if frozen at rates that are commonly observed in pavement systems (0.1 to 1.0 inches/day) and if free water is available (less than 5 to 10 feet below the freezing front). Figure 2-2 shows results of laboratory frost-susceptibility tests performed using a standardized freezing procedure on 6-inch high by 6-inch diameter specimens of soils ranging from well-graded gravels to fat clays. The soils that were tested are representative of materials found in frost areas. Test specimens were frozen with water made available at the base; this condition is termed "open-system" freezing, as distinguished from "closed-system" freezing in which an impermeable base is placed beneath the specimen and the total amount of water within the specimen does not change during the test. Appendix A contains a summary of results from freezing tests on natural soils. The data in appendix A can be used to estimate the relative frost-susceptibility of soils using the following two-step procedure: 1) select at least two soils having densities and grain-size distributions (the 0.074-, 0.02- and 0.01-millimeter sizes are most critical) similar to the soil in question, and 2) estimate the frost-susceptibility of that soil from those of the two similar soils.

(1) Diagrams a through d in figure 2-2 show individual test results for each of the four major soil groups: gravels, sands, silts, and clays. A family of overlapping envelopes is given in figure 2-3 showing the laboratory test results by various individual soil groupings, as defined by MIL-STD-619(CE). A frost-susceptibility adjective classification scale, relating the degree of frost-susceptibility to the exhibited laboratory rate of heave, is shown at the left side of figure 2-3. Because of the severity of the laboratory test, the rates of heave shown in figures 2-2 and 2-3 are generally greater than may be expected under normal field conditions. Soils that heave in the standard laboratory tests at average rates of up to 1 millimeter per day are considered satisfactory for use under pavements in frost areas, unless unusually severe conditions of moisture availability and temperature are anticipated.

(2) It can be seen in figures 2-2 and 2-3 that soils judged as non-frost-susceptible under the criteria given are not necessarily free of susceptibility to frost heaving. Also, soils that, although

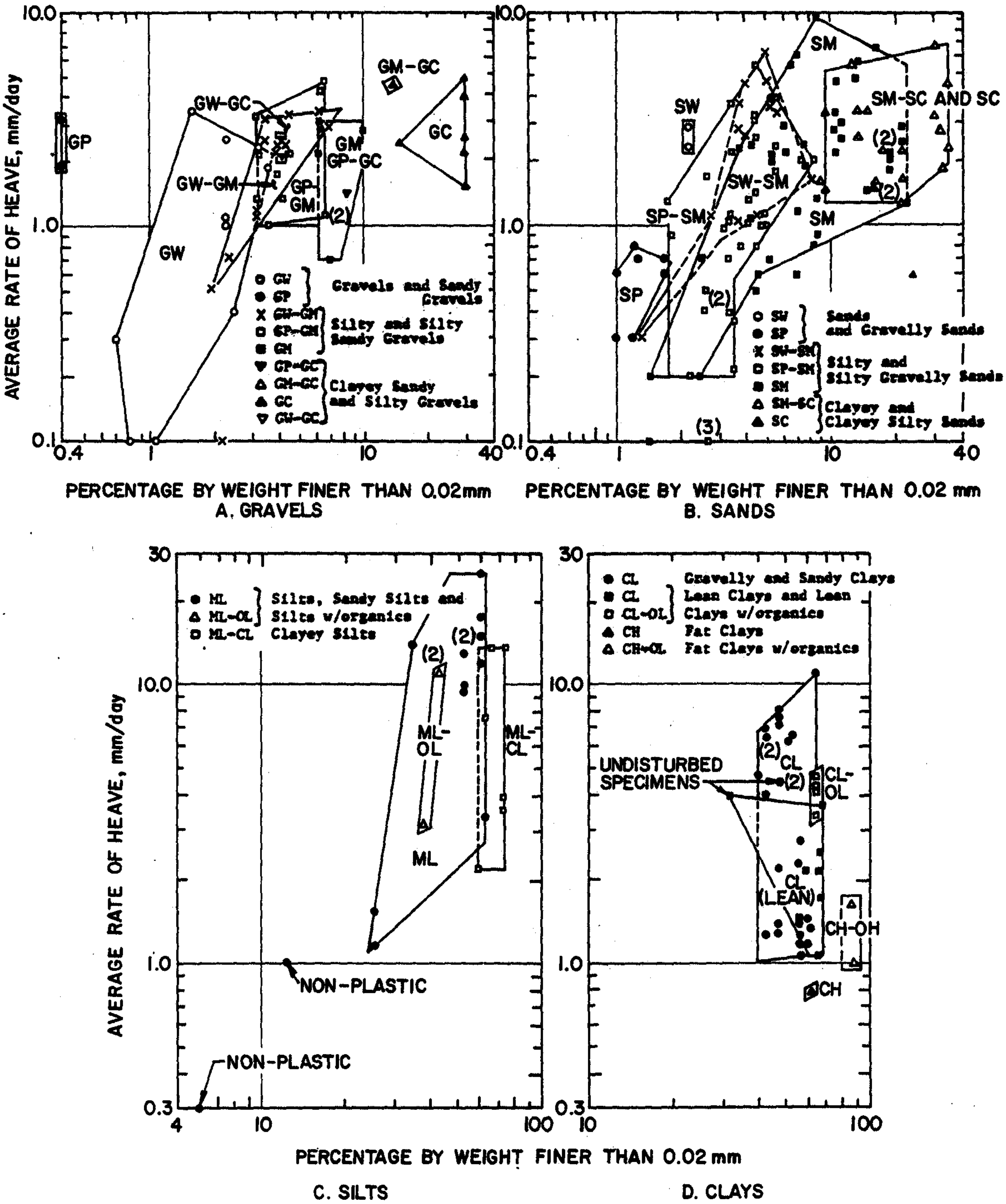

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FIGURE 2-2. RATES OF HEAVE IN LABORATORY FREEZING TESTS ON REMOLDED SOILS

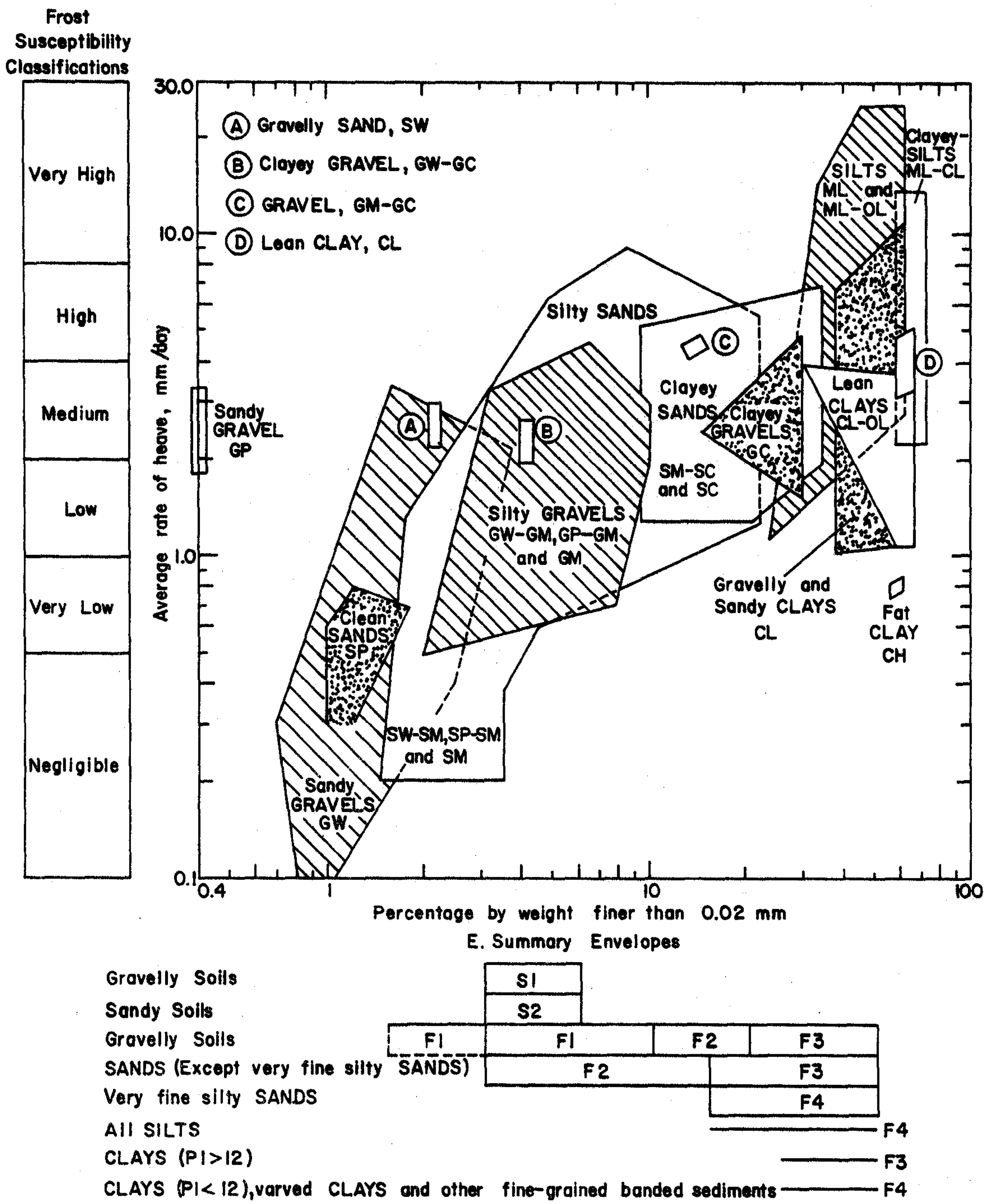

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FIGURE 2-3 . RATES OF HEAVE IN LABORATORY FREEZING TESTS ON REMOLDED SOILS indicated to be of negligible frost-susceptibility, approach a rate of heave of 1.0 millimeter per day in laboratory tests should be expected to show some measurable frost heave under average field conditions. These facts must be kept in mind when applying the criteria to other-than-normal pavement practice, and when considering subsurface drainage measures.

b. Frost-susceptibility classification. For frost design purposes, soils are divided into eight groups as shown in table 2-1. The first four groups are generally suitable for base course and subbase course materials, and any of the eight groups may be encountered as subgrade soils. Soils are listed in approximate order of decreasing bearing capacity during periods of thaw. There is also a tendency for the order of the listing of groups to coincide with increasing order of susceptibility to frost heave, although the low coefficients of permeability of most clays restrict their heaving propensity. The order of listing of subgroups under groups F3 and F4 does not necessarily indicate the order of susceptibility to frost heave of these subgroups. There is some overlapping of frost-susceptibility between groups. Soils in group F4 are of especially high frost-susceptibility.

(1) The S1 group includes gravelly soils with very low to medium frost-susceptibility classifications that are considered suitable for subbase materials. They will generally exhibit less frost heave and higher strength after freeze-thaw cycles than similar F1 group subgrade soils. The S2 group includes sandy soils with very low to medium frost-susceptibility classifications that are considered suitable for subbase materials. Due to their lower percentages of finer-than-0.02-millimeter grains than similar F2 group subgrade soils, they will generally exhibit less frost heave and higher strength after freeze-thaw cycles.

(2) The F1 group is intended to include frost-susceptible gravelly soils that in the normal unfrozen condition have traffic performance characteristics of GM, GW-GM, and GP-GM type materials with the noted percentages of fines. The F2 group is intended to include frost-susceptible soils that in the normal unfrozen condition have traffic performance characteristics of GM, GW-GM, GP-GM, SM, SW-SM, or SP-SM type materials with fines within the stated limits. Occasionally, GC or SC materials may occur within the F2 group, although they will normally fall into the F3 category. The basis for division between the F1 and F2 groups is that F1 materials may be expected to show higher bearing capacity than F2 materials during thaw, even though both may have experienced equal ice segregation.

(3) Varved clays consisting of alternating layers of silts and clays are likely to combine the undesirable properties of both silts and clays. These and other stratified fine-grained sediments may be hard to classify for frost design. Since such soils are likely to

Table 2-1. Frost design soil classification.

Frost group		Kind of soil	Percentage finer than 0.02 mm by weight	Typical soil types under Unified Soil Classification System
NFS**	(a)	Gravels Crushed stone Crushed rock	0-1.5	GW, GP
	(b)	Sands	0-3	SW,SP
PFS	(a)	Gravels Crushed stone Crushed rock	1.5-3	GW,GP
	(b)	Sands	3-10	SW,SP
S1		Gravelly soils	3-6	GW, GP, GW-GM, GP-GM
S2		Sandy soils	3-6	SW, SP, SW-SM, SP-SM
F1		Gravelly soils	6 to 10	GM, GW-GM, GP-GM
F2	(a)	Gravelly soils	10 to 20	GM, GW-GM, GP-GM,
	(b)	Sands	6 to 15	SM, SW-SM, SP-SM
F3	(a)	Gravelly soils	Over 20	GM, GC
	(b)	Sands, except very fine silty sands	Over 15	SM, SC
	(c)	Clays, PI less than 12	-	CL, CH
F4	(a)	All silts	-	ML, MH
	(b)	Very fine silty sands	Over 15	SM
	(c)	Clays, PI greater than 12	-	CL, CL-ML
	(d)	Varved clays and other fine-grained, banded sediments	-	CL and ML; CL, ML, and SM; CL, CH, ML and SM

** Non-frost-susceptible.
Possibly frost-susceptible, but requires laboratory test to determine frost design soil classification.

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heave and soften more readily than homogeneous soils with equal average water contents, the classification of the material of highest frost-susceptibility should be adopted for design. Usually, this will place the over-all deposit in the F4 category.

(4) Under special conditions, the frost group classification adopted for design may be permitted to differ from that obtained by application of the above frost group definitions. The difference is not to be greater than one frost group number justification for such differences should take into account special conditions of subgrade moisture or soil uniformity, in addition to soil gradation and plasticity, and should include data on performance of existing pavements near those proposed to be constructed.

2-5. Frost heaving. Frost heave, manifested by the raising of the pavement, is directly associated with ice segregation and is visible evidence on the surface that ice lenses have formed in the subgrade, in the base material, or in both. Detrimental frost heave can be effectively controlled by designing the pavement so that frost will penetrate to only a limited depth into frost-susceptible subgrade soil and by adequate subgrade preparation and transition details. If significant freezing of a frost-susceptible subgrade does occur, the heave may be uniform or nonuniform, depending on variations in the character of the soils and the ground water conditions underlying the pavement and the thermal properties of the paving materials.

a. Uniform heave. Uniform heave is the raising of adjacent areas of a pavement surface by approximately equal amounts. The initial shape and smoothness of the surface remain substantially unchanged. Conditions conducive to uniform heave may exist, typically, in a homogeneous section of pavement that is exposed to equal solar radiation and is constructed with a fairly uniform stripping or fill depth, and that has uniform ground water depth and horizontally uniform soil characteristics.

b. Nonuniform heave. Nonuniform heave causes objectionable unevenness or abrupt changes in grade at the pavement surface. Conditions conducive to irregular heave occur, for example, at changes in pavement types or sections, at locations where subgrades vary between clean non-frost-susceptible sands and silty frost-susceptible materials, at abrupt transitions from cut to fill sections with the ground water close to the surface, or where excavation cuts into water-bearing strata. On pavements with inadequate frost protection, some of the most severe pavement roughness is caused by differential heave at abrupt changes in subgrade soil type and at drains and culverts and by boulder heaves. Special techniques of subgrade preparation and adequate transition details are needed to minimize irregular heave from these causes.

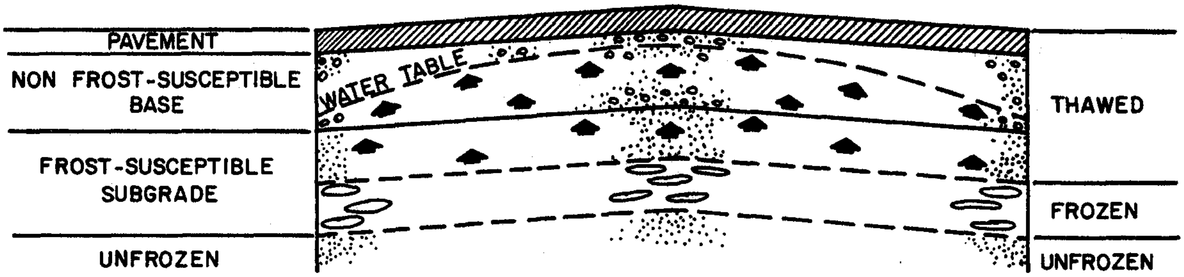

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FIGURE 2-4. MOISTURE MOVEMENT UPWARD INTO BASE COURSE DURING THAW

c. Supporting capacity may be reduced in clay subgrades even though significant heave has not occurred. Overconsolidation in clay soils occurs due to negative pressures generated in the freezing zone. As a result, the clay particles are reoriented into a more compact aggregated or layered structure with the clay particles and ice being segregated. The resulting consolidation may largely balance the volume of the ice lenses formed. Even clays that show no evidence of ice segregation, measurable moisture migration, or significant volume increase when frozen may significantly lose supporting capacity during the thaw period.

d. If frost-susceptible soil beneath a pavement will freeze, the effect of the reduced supporting capacity during frost-melting periods must be taken into account in designing the layered pavement structure.